# Effect of Temperature on the Deformation Behavior of B2 Austenite in a Polycrystalline $Ni_{49.9}Ti_{50.1}$ (at.%) Shape Memory Alloy


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## Introduction

Superelasticity in austenitic B2-NiTi is of great technical interest and has been studied in the past by several researchers [1]. However, investigation of temperature dependent deformation in B2-NiTi is equally important since competing mechanisms of stress-induced martensite (SIM), retained martensite, plastic and deformation twinning can lead to unusual mechanical behaviors. Identification of the role of various mechanisms contributing to the overall deformation response of B2-NiTi is imperative to understanding and maturing SMA-enabled technologies. Thus, the objective of this work was to study the deformation of polycrystalline $Ni_{49.9}Ti_{50.1}$ (at. %) above $A_f$ (105 ºC) in the B2 state at temperatures between 165–440 ºC, and generate a B2 deformation map showing active deformation mechanisms in different temperature-stress regimes.

## Experimental Results

The material used in this study was a binary $Ni_{49.9}Ti_{50.1}$ (at.%) alloy with stress-free transformation temperatures ($M_s$, $M_f$, $A_s$ and $A_f$) of 71, 55, 92, and 105 ± 2 °C, respectively [2]. Several techniques were used for this study: *in-situ* and *ex-situ* mechanical testing, *in-situ* neutron diffraction, room-temperature and hot-stage transmission electron microscopy, and elasto-plastic self-consistent (EPSC) polycrystalline deformation modeling based on grain-level dislocation plasticity [3]. *In-situ* neutron diffraction experiments were carried out using SMARTS and HIPPO diffractometers at the Los Alamos Neutron Science Center. Four different samples, one each for 165, 230, 290 and 320 º C analyses, were used for *in-situ* testing. Each sample was isothermally loaded in uniaxial tension to 18% strain and diffraction data were acquired at a minimum of 10 different strain values. The level of SIM, determined from the neutron diffraction data, was found to vary with temperature, saturating at a martensite volume fraction ($V_f$) of 0.25 at 165 ºC and 230 ºC, and 0.13 at 290 ºC. No martensite was observed at 320 ºC (Fig. 1a). After unloading, an average $V_f$ of 0.12 was stabilized for samples tested at 165, 230, and 290 ºC. Beyond the 0.5% elastic strain limit, hkl-specific lattice strains deviated from linearity and were very dependent on orientation (Fig. 1b) and temperature. In all cases, $\{111\}_{B2}$ planes yielded first and accommodated the lowest strain, followed by $\{110\}_{B2}$ planes that accommodated intermediate strain, and $\{100\}_{B2}$ planes that accommodated the maximum strain. In addition, in the loading direction, $\{110\}_{B2}$ texture gradually increased and $\{111\}_{B2}$ texture gradually decreased with increasing

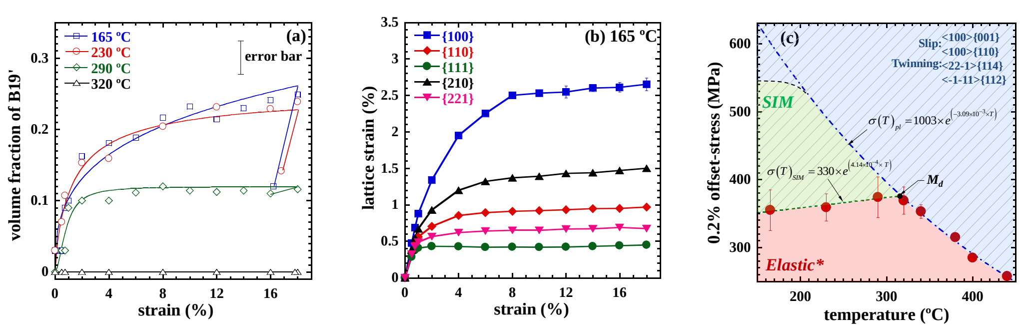


*Figure 1: (a) Stress-induced martensite phase fractions during loading and unloading of $Ni_{49.9}Ti_{50.1}$ at various temperatures, (b) Lattice strains associated with planes perpendicular to the loading axis at 165 ºC, (c) Deformation-stress map showing the mechanisms responsible for the stress-strain behavior.*

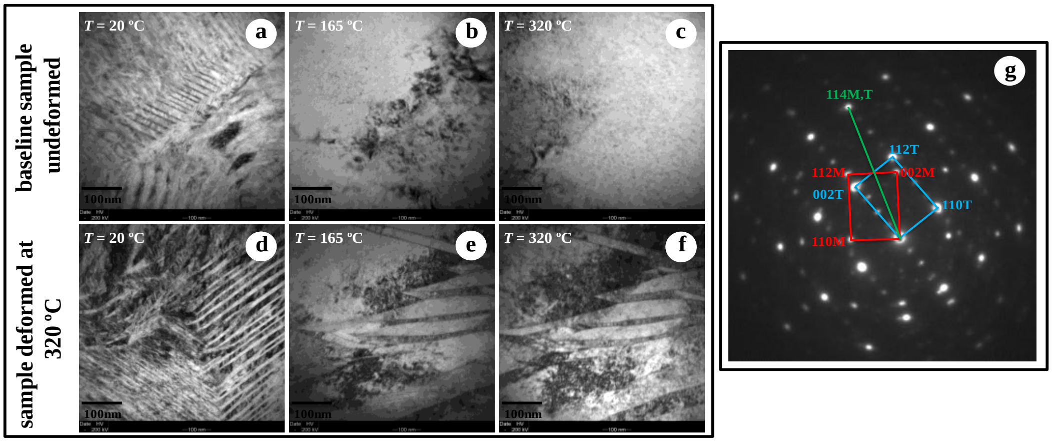


*Figure 2: TEM bright-field (BF) images of the microstructure of $Ni_{49.9}Ti_{50.1}$ at 20, 165 and 320 ºC for the virgin sample (a, b, and c, respectively), and sample post-deformed to 18% strain at 320 ºC (d, e, and f). (g) Selective area diffraction pattern (SADP) of the planar faults observed after deformation.*

strain for all the samples. Both the lattice strains and texture effects were more pronounced at lower temperatures than at 320 ºC.

Hot-stage TEM was conducted on the as-received sample and on 18% deformed samples tested at 165 ºC and 320 ºC. The results for only the as-received sample and the 320 ºC-tested sample are shown in Fig. 2(a-f)). The as-received sample showed self-accommodating martensite at room temperature and austenite at higher temperatures. The 165 ºC-tested sample showed martensite at room temperature, and SIM, deformation twins, and a high density of dislocations at 165 ºC and 320 ºC. The 320 ºC-tested sample, showed no SIM but only deformation twins and a high density of <100> dislocations above $A_f$. The deformation twins were determined to be compound $\{114\}_{B2}$ twins by SADP analysis (Fig. 2g).

Only the 320 ºC sample was considered for the EPSC modeling since it had no SIM. Four cases with 3 different slip systems and 2 different twin systems were formulated in various combinations. It should be mentioned that no diffusion assisted deformation processes were considered in this model. The case that closely predicted the stress-strain response and experimental neutron diffraction results of texture and lattice strains was the one which contained both <100> slip and <22-1>{114} and <-1-11>{112} deformation twins.

Based on the experimental and modeling results, a B2-NiTi deformation map was constructed that highlights elastic, SIM and plastic regions in the 0.2% offset stress and temperature space (Fig. 1c). The boundary lines were formulated based on the experimental data using exponential functions, and the martensite desist temperature, $M_d$, was determined from this map as shown in Fig. 1c. More details can be found in Ref. [2].

## Conclusions

Isothermal deformation of B2-$Ni_{49.9}Ti_{50.1}$ (at. %) to 18% strain at temperatures between 165–440 ºC consisted of recoverable strains from elastic and SIM and irrecoverable strains from retained SIM, $\langle 100\rangle_{B2}$ slip and $\{114\}_{B2}$ deformation twins. A $\{110\}_{B2}$ texture developed during deformation and lattice strain partitioning was observed with $\{100\}_{B2}$ accommodating the maximum strain. The $M_d$ temperature was determined to be between 310-320 ºC. Above this temperature, no SIM was observed and the deformation was due to slip and deformation twins only. A deformation map outlining different deformation regimes was generated.

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